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ABSTRACT

This study analyzes the meteorological environment associated with the accident of Voepass Flight 2283, involving an ATR 72-500 aircraft, which occurred on 9 August 2024 in the municipality of Vinhedo, São Paulo, Brazil. The objective was to characterize, in an integrated and multiscale approach, the atmospheric conditions favorable to severe in-flight icing, correlating meteorological evidence with the operational records described in the preliminary report issued by CENIPA. The methodology was based on ERA5 data from pressure and surface levels, GOES-16 infrared satellite imagery, polarimetric radar products, and radiosonde observations from Campo de Marte (SBMT). Temperature, relative humidity, wind, geopotential, and vertical velocity fields were analyzed between 8 and 9 August 2024, with emphasis on the critical period from 15:00 to 17:00 UTC. The results indicate that the event occurred under the influence of a frontal system associated with low-level cold-air advection, a well-defined 500 hPa trough, and upper-level dynamic support at 250 hPa, configuring a synoptic environment classically favorable to extensive cold stratiform cloud layers. The aircraft remained at the FL170 cruise level, embedded within a deep atmospheric layer characterized by temperatures between 0 °C and -20 °C and high relative humidity, a critical thermodynamic range for the presence of supercooled liquid water.

Keywords: ATR 72-500; Aircraft Accident; Frontal System; Supercooled Water; Ice Formation.

1. INTRODUCTION

The safety of aviation operations is strongly conditioned by several factors, among which meteorological conditions play a central role, particularly in regions and altitudes where adverse atmospheric phenomena may compromise the aerodynamic performance of aircraft (Cao et al., 2018; Long, 2022; Kováčiková et al., 2025; Koçyiğit, 2025). Among these phenomena, in-flight icing is recognized as one of the most critical meteorological hazards for aviation, especially for turboprop aircraft operating in the mid-levels of the troposphere, where

temperatures near 0 °C coexist with high concentrations of supercooled liquid water (Politovich, 1989; Cao et al., 2018; Gultepe et al., 2019).

In-flight icing (aircraft icing) occurs when supercooled water droplets collide with aircraft surfaces and freeze instantaneously, causing significant changes in aerodynamic geometry, increased drag, reduced lift, and degradation of overall aircraft performance (Cao et al., 2018; Shinan et al., 2019; Ruan, 2023). Even aircraft certified to operate in icing conditions may face severe limitations when exposed to environments classified as severe icing, in which protection and de-icing systems may prove insufficient (He et al., 2023; Rekuviene et al., 2024; Wu et al., 2024).

Several studies (Bernstein et al., 2005; Liu et al., 2024; Louka et al., 2024; Wen et al., 2025) show that severe icing episodes are frequently associated with specific meteorological systems, such as cold fronts, extratropical cyclones, low-pressure systems, and extensive stratiform cloud layers with high liquid water content. Under these conditions, the presence of supercooled large droplets (SLD) represents a particularly hazardous factor, as it favors the formation of clear ice, which adheres more efficiently to aircraft surfaces and is more difficult to remove by conventional de-icing systems (Takahashi et al., 2020; Cao & Xin, 2024; Guo et al., 2024).

Safety reviews indicate that a significant fraction of accidents in commercial and regional aviation between 1981 and 2010 involved icing as an important contributing factor, with many events classified as Loss of Control in Flight (LOC-I) following progressive performance degradation (Lynch and Khodadoust, 2001; Cao et al., 2015; Cao, Tan and Wu, 2018; Wang et al., 2021; Bromfield et al., 2023). Studies of accidents involving both jet and turboprop aircraft show a typical sequence: ice accumulation increases drag and drives the aircraft toward stall speed; the autopilot maintains altitude with increased nose-up attitude (positive pitch), gradually eroding the speed margin, leading to stall and sudden roll upset (Lynch and Khodadoust, 2001; Golding, 2004; Cao et al., 2015; Cao, Tan and Wu, 2018). Golding (2004) demonstrates that, under icing conditions, turboprop aircraft in cruise or holding patterns experience progressive speed reduction, followed by activation of stall protection systems and, subsequently, sudden loss of control, a dynamic that closely resembles the pattern observed in accidents involving the aircraft family considered in this study.

Studies indicate that polar air incursions over South America, often in the form of cold fronts, can advance rapidly toward subtropical and even tropical latitudes, producing severe frost events in southern, southeastern, and central Brazil (Hamilton & Tarifa, 1978; Vera & Vigliarolo, 2000; Marengo et al., 2000; Sprenger et al., 2013; Müller et al., 2015; Alves et al., 2017; Collazo & García-Herrera, 2024). These episodes are more frequent during the austral winter and are associated with large-amplitude troughs at mid-levels and post-frontal cold anticyclones that

channel polar air northward east of the Andes (Vera & Vigliarolo, 2000; Marengo et al., 2000; Sprenger, Martius & Arnold, 2013; Müller et al., 2015; Collazo & García-Herrera, 2024). These same configurations, intense frontal systems, strong thermal gradients, and cold air advection, are precisely those that, in other regions, are identified as typical environments for severe aircraft icing, characterized by thick stratiform clouds, high supercooled liquid water content, and SLD behind cold fronts (Cao et al., 2018; Casqueiro et al., 2023; Liu et al., 2024; Wen et al., 2025).

The accident involving the Voepass ATR 72-500 aircraft, which occurred on August 9, 2024, at 16:22 UTC (13:22 local time) in the municipality of Vinhedo (SP), falls within this complex meteorological context. Preliminary information indicates the presence of severe icing along the flight route, with active meteorological warnings and reports from other aircraft encountering similar conditions in the same region and time period. Data extracted from flight recorders and initial technical analyses suggest a progressive degradation of aircraft performance associated with icing, culminating in loss of control in flight, an outcome widely documented in the international literature on severe in-flight icing (CENIPA, 2024).

Given this scenario, it becomes essential to systematically investigate the meteorological conditions present on the day of the accident. A detailed understanding of the atmospheric processes involved not only contributes to clarifying this specific event but also provides valuable insights for improving aviation weather forecasting.

Thus, the present study aims to analyze the meteorological conditions that contributed to the Voepass ATR 72-500 accident, with emphasis on characterizing the atmospheric environment favorable to severe icing, establishing a correlation between observed data, operational records, and conceptual models described in the scientific literature on aviation meteorology.

2. MATERIALS AND METHODS

This study was developed using an observational and documentary approach, designed as a case study, with the objective of analyzing, in an integrated manner, the meteorological conditions associated with the accident involving the ATR 72-500 aircraft, Voepass Linhas Aéreas Flight 2283, which occurred on August 9, 2024, in the municipality of Vinhedo, in the state of São Paulo, Brazil

2.1. Study Area

The study area comprises the southern and southeastern regions of Brazil (Figure 1), with emphasis on the air corridor between the western part of Paraná State and the interior of São Paulo State, including the region of Vinhedo (SP), where the analyzed accident occurred.

According to Alvares et al. (2013), the region is predominantly characterized by well-defined climate types: Cfa (humid subtropical oceanic climate, without a dry season and with hot summers), Cwa (humid subtropical oceanic climate, without a dry season and with temperate summers), and Cfb (humid subtropical oceanic climate with dry winters and warm summers). These climate types are characterized by the absence of a well-defined dry season, a high frequency of frontal systems, and significant thermal variability during winter, with frequent incursions of cold air masses (Garreaud, 2000; Alvares et al., 2013; Dubreuil et al., 2019).

The region is frequently affected by cold fronts associated with extratropical cyclones that develop over southern South America and move toward the Atlantic Ocean (Reboita et al., 2010). Studies show that the corridor between southern Brazil and the Antarctic Peninsula is one of the main cyclogenetic regions in the Southern Hemisphere, with frequent formation of extratropical cyclones and cold fronts that propagate over the Atlantic and impact the continent (Gandra & De Quadro, 2021). These extratropical cyclones develop in a baroclinic environment, where strong horizontal temperature gradients favor the formation of mid-level troughs and large-scale waves (Gandra & De Quadro, 2021; Federer et al., 2025).

During winter, midlatitude storm activity in the Southern Hemisphere intensifies, with stronger extratropical cyclones and enhanced heat and moisture transport, increasing the continental reach of associated frontal systems (Raible et al., 2021; Chemke et al., 2022; Yao et al., 2023). These systems promote cold air advection at low levels and deepening of troughs at 500 hPa, often coupled with upper-level jets, which enhances vertical wind shear and forced ascent (Chen & Li, 2019; Yao et al., 2023).

2.2. Aircraft

The aircraft involved in the accident analyzed in this study is an ATR 72-500 (Figure 2), a regional turboprop, certified for operations in icing conditions and widely used on short- and medium-haul domestic routes. The ATR 72-500 is equipped with specific systems for ice detection, protection, and mitigation, designed to ensure safe operation in cold and humid atmospheric environments, as documented in technical reports from the Brazilian Aeronautical Accident Investigation and Prevention Center (CENIPA, 2024).

High-wing, lower-speed turboprop aircraft such as the ATR 72-500 are more susceptible to ice accretion due to their operational envelope, the type of ice protection systems employed, as well as their aerodynamic profile and de-icing mechanisms (Ratvasky et al., 2010). These factors result in longer exposure times to supercooled droplets compared to jet aircraft (Liu et al., 2025; Wang et al., 2025; Müller et al., 2025). The aforementioned studies provide a technical basis for a better understanding of the physical and operational processes involved.

2.3. Data

2.3.1. Satellite Imagery

The atmospheric conditions associated with the event were analyzed using geostationary satellite imagery, with the objective of characterizing cloud cover, the structure of the active meteorological systems, and the temporal evolution of the synoptic and mesoscale environment.

To monitor the meteorological system, satellite images were obtained from the archive of the Division of Meteorological Satellites and Sensors (DISSM/CPTEC) of the National Institute for Space Research (INPE) (<https://ftp.cptec.inpe.br/goes/goes16/retangular/>). The images correspond to the infrared channel (IR – 10.35 μm) of the GOES-16 satellite, acquired by the Advanced Baseline Imager (ABI) sensor, with a spatial resolution of 2 $\times$ 2 km and a temporal resolution of 10 minutes, covering August 9, 2024.

2.3.2. Reanalysis

Two sets of reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used, with a spatial resolution of 0.25° in latitude and longitude and an hourly temporal resolution, covering the period from August 8 to 9, 2024. The datasets were generated using atmospheric and flux fields derived from the ERA5 numerical weather prediction and data assimilation system, which represents the fifth generation of the European reanalysis for global weather and climate conditions (Hersbach et al., 2020).

In the first dataset, the following variables were used: air temperature ($^{\circ}\text{C}$), relative humidity (%), zonal (u) and meridional (v) wind components (m s^{-1}), vertical velocity (ω , Pa s^{-1}), and geopotential ($\text{m}^2 \text{s}^{-2}$) from pressure levels ranging from 1000 to 200 hPa (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels>).

In the second dataset, the following variables were used: mean sea level pressure, 2-m air temperature ($^{\circ}\text{C}$), 2-m relative humidity (%), and 10-m meridional wind component (m s^{-1}), corresponding to single levels (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels>).

2.3.3. Weather Radar

Data from the meteorological radar located in Salesópolis, São Paulo (23.60° S; 45.97° W), operated by the Centro Tecnológico de Hidráulica (CTH), were used for August 9, 2024. The system is an S-band polarimetric radar, suitable for characterizing the three-dimensional structure of precipitation and hydrometeor microphysics. The following polarimetric fields were analyzed: reflectivity (dBZ), differential reflectivity (ZDR, in dB), and specific differential phase (KDP, in ° km⁻¹). These variables were evaluated using the Plan Position Indicator (PPI) product, at the second elevation angle of the volume scan (1.6°), corresponding to the atmospheric layer where the aircraft was located at the time of the accident. This configuration is particularly useful for identifying the spatial organization of precipitation and the homogeneity of hydrometeors. Specifically, the radar beam intercepted the layer between approximately 4 and 6 km at the analyzed distances, close to FL170 (~5.2 km), allowing the characterization of precipitation structure within the layer of interest. The analyzed data cover the period from 15:00 to 15:15 UTC, coinciding with the critical operational window of the flight. The instantaneous position of the aircraft, obtained from publicly available ADS-B tracking data, was overlaid onto the radar fields to enable a localized analysis between the flight trajectory and the observed precipitation structure.

2.3.4. Cenipa Data

Information regarding the aeronautical occurrence analyzed in this study was obtained from official documents produced by the Brazilian Aeronautical Accident Investigation and Prevention Center (CENIPA), the central authority of the Aeronautical Accident Investigation and Prevention System (SIPAER), responsible for conducting aircraft accident investigations in Brazil.

The data sources included the Preliminary Report of the occurrence, technical documents made available through the CENIPA Portal, as well as official transcripts and presentations related to the investigation of the accident involving the ATR 72-500 aircraft, which occurred on August 9, 2024, in the municipality of Vinhedo (SP), Brazil. According to the principles established by Annex 13 to the Convention on International Civil Aviation, investigations conducted by CENIPA are non-punitive in nature, with the primary objective of identifying contributing factors and issuing safety recommendations, rather than determining blame or legal liability. Therefore, the information obtained from these documents was used exclusively for the technical contextualization of the event and for integration with the meteorological analysis carried out in this study.

Particular attention was given to the timing and sequence of events associated with the identification of icing conditions, activation of anti-icing and de-icing systems, alerts issued by the Aircraft Performance Monitoring (APM) system, and the moments preceding the loss of control of the aircraft. These data were used as temporal references for joint analysis with meteorological fields derived from satellite imagery and atmospheric reanalysis data.

These datasets included descriptions of the Ice Detection System, anti-icing and de-icing systems, as well as the functioning of the APM system, which monitors aircraft performance degradation under icing conditions. The information was used to contextualize operational thresholds and alerts recorded during the flight, without attributing causality, allowing for an integrated analysis between the observed atmospheric environment and the reported operational parameters (e.g., Yamazaki et al., 2021).

2.3.5. Radiosonde

Considering the spatial proximity and synoptic representativeness relative to the area of the occurrence, the radiosonde observation conducted at Campo de Marte Aerodrome (SBMT), in São Paulo, at 12:00 UTC on August 9, 2024, was prioritized. This station was selected due to its better coverage and its upstream location relative to the accident area, under the same atmospheric configuration associated with the passage of a frontal system. These data were obtained from the Department of Atmospheric Science at the University of Wyoming (https://weather.uwyo.edu/upperair/sounding_legacy.html).

3. RESULTS

In the context of the aeronautical investigation conducted by CENIPA, the phenomenon associated with the presence of severe in-flight icing is referred to as High-Altitude Icing Formation (FGA). From a physical and meteorological perspective, this term corresponds to what is described in the international literature as severe in-flight icing, characterized by the presence of cold clouds with high supercooled liquid water content and prolonged aircraft exposure to subfreezing temperatures. Throughout this study, both terms are used equivalently, in accordance with the terminology adopted in official documents and in the scientific literature (Liu et al., 2024). Figure 3a presents a conceptual diagram of the vertical evolution of Flight 2283 as a function of time (UTC), highlighting the aircraft's persistence at different flight levels during the critical operational phase. It is observed

that, after takeoff, the aircraft gradually ascended and reached the cruising level FL170, corresponding to approximately 510 hPa, where it remained for most of the period between 15:23 and 16:22 UTC.

The figure shows that this flight level was embedded within an atmospheric layer characterized by subfreezing temperatures, well above the 0 °C level, which was located at mid-to-lower tropospheric levels, approximately between 700 and 750 hPa. At FL170 (~500–520 hPa), temperatures were around –9 °C, as indicated on the right side of the diagram. The continuous presence of the aircraft within this thermal range, combined with the high humidity observed in the atmospheric analyses, characterizes an environment favorable for in-flight icing.

It is also noteworthy that, throughout the represented time window, there is no indication of a rapid transition to thermodynamically warmer layers; instead, the aircraft remained exposed to the core of the cold layer, a feature consistent with the progressive nature of the operational records described by CENIPA. The figure thus synthesizes the relationship between the vertical evolution of the flight and the thermal structure of the atmosphere during the critical period of the event.

Additionally, Figure 3b presents the observed temporal profile of altitude and velocity, confirming the prolonged persistence of the aircraft at FL170 during the critical interval. The agreement between the operational records and the schematic representation reinforces the consistency of the temporal exposure to the previously characterized atmospheric environment.

Figure 4 presents the temporal evolution of mean sea level pressure and 10-m wind between 12:00 and 18:00 UTC on August 9, 2024. At 12:00 UTC (Figure 4a), a well-defined frontal system is observed advancing from southern Brazil toward the Southeast, characterized by a strong horizontal pressure gradient and predominantly south/southwesterly flow over Paraná and parts of São Paulo. This pattern indicates the advection of colder and denser air at low levels, typical of polar incursions during the austral winter.

Between 15:00 and 16:00 UTC (Figures 4b and 4c), the pressure gradient intensifies over southern and southeastern Brazil, with the frontal axis positioned approximately along the Cascavel–Guarulhos flight corridor. The 10-m wind field shows the persistence of south/southwesterly winds, favoring the maintenance of cold and moist air at low levels in the region. During this period, the surface circulation suggests an active dynamical environment, with low-level convergence associated with the frontal zone.

At 18:00 UTC (Figure 4d), although the frontal system shows initial signs of eastward displacement, the synoptic pattern still indicates the presence of post-frontal cold air over much of southern and southeastern Brazil. The gradual weakening of the pressure gradient suggests a transition to a more mature stage of the system, yet maintaining atmospheric conditions favorable for extensive and persistent stratiform cloudiness in the rear of the cold front.

The synoptic pattern depicted in Figure 4 is consistent with atmospheric configurations frequently associated with severe aircraft icing, as described in several studies in the scientific literature. The presence of an intense cold front, accompanied by strong low-level cold air advection, constitutes one of the main mechanisms responsible for the formation of extensive cold stratiform cloud layers, an environment classically favorable for the presence of supercooled liquid water (Bernstein et al., 2005; Cao et al., 2018; Louka et al., 2024).

In particular, cold fronts associated with polar air incursions during the austral winter in South America are often responsible for the formation of extensive areas of persistent stratiform cloudiness in the post-frontal region, with subfreezing temperatures prevailing at mid-tropospheric levels (Vera & Vigliarolo, 2000; Marengo et al., 2002; Sprenger et al., 2013). These conditions are analogous to those observed in international case studies of severe in-flight icing, in which the combination of cold air, high moisture content, and sustained synoptic forcing results in environments conducive to severe in-cloud icing (Cao et al., 2015; Liu et al., 2024; Wen et al., 2025).

The temporal coincidence between the intensification of the pressure gradient and the position of the cold front over the flight route during the aircraft's cruise phase is particularly relevant from an operational perspective. Unlike isolated convective systems, stratiform frontal systems tend to produce extensive and continuous hazard areas, significantly reducing the possibilities for lateral deviation and increasing the likelihood of prolonged aircraft exposure to adverse conditions (Golding, 2004; Gultepe et al., 2019).

During the period of Flight 2283, a SIGMET for severe High-Altitude Icing Formation (FGA) was in effect over southern and southeastern Brazil, forecasting occurrence between FL120 and FL210, a range that fully encompasses the FL170 flight level used by the aircraft.

The SIGMET remained active throughout the entire critical operational window of the flight, coinciding temporally with the records of progressive performance degradation described in the CENIPA preliminary report.

The correspondence between the altitudinal range indicated in the meteorological warning and the actual flight level of the aircraft suggests that the flight occurred under meteorological conditions previously identified as potentially hazardous for aviation operations.

Figure 5 presents the spatial distribution of temperature and relative humidity at 850 hPa at 1500, 1600, and 1700 UTC on August 9, 2024, a period that coincides with the cruise phase of Flight 2283 and the onset of the progressive performance degradation described in the CENIPA preliminary report. At 1500 UTC (Figure 5a), an extensive area of subfreezing and near -0 °C temperatures is observed advancing from Paraná toward the interior of São Paulo State, accompanied by high relative humidity values exceeding 80% along the Cascavel–Guarulhos flight corridor.

Between 1600 and 1700 UTC (Figures 5b and 5c), this cold and moist plume intensifies and remains nearly stationary over southeastern Brazil, including the region near Vinhedo (SP). The persistence of high relative humidity associated with subfreezing temperatures at 850 hPa indicates the presence of a cold and saturated air mass in the lower troposphere, a condition favorable for the maintenance of extensive and thick stratiform cloud layers. This environment is consistent with the continuous presence of supercooled liquid water at slightly higher levels, often associated with aircraft icing in turboprop operations (Bernstein et al., 2005; Cober & Isaac, 2012).

The relationship between this thermodynamic pattern and the aircraft’s persistence at cruise level suggests that the flight remained, for a prolonged period, within a persistently cold and moist atmospheric environment, a condition that significantly increases the likelihood of progressive ice accretion.

The temperature and humidity fields at 850 hPa shown in Figure 5 provide important meteorological evidence that directly aligns with the operational observations described by CENIPA. According to the preliminary report, the aircraft was operating near FL170, within the altitudinal range (12,000–21,000 ft) for which a severe icing warning had been issued, and exhibited signs of progressive performance degradation prior to the loss of control. The presence of a cold and highly moist air mass at 850 hPa suggests that this cold and moist structure extended vertically into the mid-troposphere, including the aircraft’s flight level, indicating that the aircraft was embedded within a layer favorable for in-cloud icing.

Classical and recent studies show that environments characterized by temperatures near or slightly below 0 °C at low levels, combined with high humidity, favor the formation of extensive cold stratiform cloud layers with high supercooled liquid water content (Politovich, 1989; Cao et al., 2018; Casqueiro et al., 2023). Under these conditions, aircraft may experience gradual ice accretion even in the absence of intense precipitation or deep convection, making the phenomenon particularly deceptive from an operational standpoint.

The spatial and temporal persistence of the cold–moist field observed between 15:00 and 17:00 UTC is consistent with the pattern described in the CENIPA report, which does not indicate an abrupt or localized event, but rather a progressive degradation of the aircraft’s aerodynamic performance. This behavior is consistent with the

mechanism widely described in the literature for accidents related to severe icing: prolonged exposure to cold stratiform environments, continuous ice accretion, gradual increase in drag, and erosion of speed margin, ultimately culminating in an abrupt aerodynamic response (Lynch & Khodadoust, 2001; Cao et al., 2015; Bromfield et al., 2023).

Figure 5 reinforces the interpretation that the atmospheric environment along the flight route not only allowed but favored the persistence of conditions conducive to in-flight icing during the critical phase of Flight 2283. This evidence complements the synoptic scenario presented in Figure 4 and establishes a direct thermodynamic link between the observed meteorological conditions and the operational effects described by CENIPA, supporting the hypothesis that icing played a significant role in the chain of events leading to the loss of control of the aircraft.

Figure 6 presents the distribution of relative humidity, regions of upward vertical motion ($\omega < 0$), and the -5°C isotherm at 700 hPa between 15:00 and 17:00 UTC on August 9, 2024. At 15:00 UTC (Figure 6a), an extensive area of high relative humidity, exceeding 80%, is observed covering much of Paraná and advancing toward the interior of São Paulo State. This moist region coincides with areas of upward vertical motion, indicating persistent lifting of the air mass at mid-tropospheric levels.

At 16:00 UTC (Figure 6b), the region of maximum humidity and ascent intensifies and becomes more organized over southeastern Brazil, positioning directly over the Cascavel-Guarulhos flight corridor. The -5°C isotherm at 700 hPa intersects this same area, indicating that the ascent is occurring within a thermodynamically favorable environment for the maintenance of supercooled liquid water droplets. This pattern persists at 17:00 UTC (Figure 6c), indicating that the atmospheric structure responsible for lifting and air saturation remained nearly stationary during the critical phase of the flight.

The combination of high relative humidity, persistent upward motion, and moderately subfreezing temperatures at 700 hPa suggests the presence of a cold, thick, and continuous stratiform layer, a condition classically associated with in-cloud icing environments. The temporal persistence of this pattern indicates that the aircraft was exposed for a prolonged period to a potentially severe atmospheric environment.

The 700 hPa layer is frequently identified in the literature as one of the most critical levels for severe aircraft icing, particularly during cruise operations of turboprop aircraft (Politovich, 1989; Bernstein et al., 2005; Gultepe et al., 2019). The simultaneous presence of high relative humidity, temperatures between approximately -5°C and -15°C , and persistent upward motion favors the formation and maintenance of supercooled liquid water in stratiform clouds, even in the absence of deep convection.

The patterns observed in Figure 6 are consistent with environments described in international case studies of accidents and incidents involving severe in-flight icing. Studies such as Golding (2004), Cao et al. (2015), and Wen et al. (2025) highlight that the most hazardous icing conditions frequently occur within cold stratiform layers associated with cold fronts, where lifting is sustained and aircraft exposure can be prolonged. Under such conditions, ice accretion tends to be gradual but continuous, making the severity of the phenomenon more difficult for the flight crew to immediately perceive.

The persistence of negative ω and high humidity between 15:00 and 17:00 UTC is directly relevant when interpreted in light of the CENIPA preliminary report. According to the report, the aircraft was cruising at FL170, within the altitudinal range (12,000–21,000 ft) for which a severe icing warning had been issued, and experienced successive performance degradation alerts prior to the loss of control. The atmospheric structure depicted in Figure 6 suggests that the flight remained embedded within an active icing layer for a significant portion of this period, consistent with the progressive nature of the degradation described in the report.

Moreover, the coexistence of persistent ascent (ω) and moderately subfreezing temperatures is particularly favorable for the formation of mixed and clear ice, types of ice known to adhere more efficiently to aircraft surfaces and to be more difficult to remove by conventional de-icing systems (Lynch & Khodadoust, 2001; Cao & Xin, 2020; Guo et al., 2024). This aspect is consistent with the operational sequence described by CENIPA, in which the aircraft maintained its flight level for a certain period while its performance margin was gradually eroded, ultimately culminating in an abrupt aerodynamic response.

Figure 7 presents the geopotential height, temperature, and wind fields at 500 hPa at 16:00 UTC on August 9, 2024, a time that coincides with the critical phase of Flight 2283 and the period immediately preceding the loss of control described in the CENIPA preliminary report. A well-defined large-scale trough is observed over

southern and southeastern Brazil, with its axis oriented approximately southwest–northeast, extending from northern Argentina to the interior of São Paulo State.

The wind field at 500 hPa shows strong flow associated with the trough, with pronounced cyclonic curvature over the region. Isotherms indicate the presence of relatively cold air at mid-levels, with temperatures sufficiently low to sustain deep cold cloud layers when combined with the moisture observed at lower levels. The trough configuration suggests an environment favorable for large-scale ascent, particularly ahead of the trough axis, where the Cascavel–Guarulhos flight corridor is located.

This mid-level structure is consistent with the persistence of upward motion fields observed at 700 hPa (Figure 6) and with the maintenance of cold stratiform cloudiness observed in satellite imagery (Figure 9), indicating dynamic coupling between mid-level, low-level, and surface-level atmospheric layers during the critical period of the flight.

The presence of a well-defined trough at 500 hPa, as shown in Figure 7, is a key element for understanding the persistence of the environment favorable to severe icing along the flight route. Studies in aviation meteorology indicate that mid-level troughs associated with frontal systems sustain large-scale ascent, promoting the maintenance of cold stratiform clouds and layers rich in supercooled liquid water (Golding, 2004; Bernstein et al., 2005; Gultepe et al., 2019).

This type of dynamic configuration is particularly relevant because it favors “diffuse” and persistent icing environments, in contrast to localized and short-lived events associated with deep convection. As highlighted by Cao et al. (2015) and Liu et al. (2024), many of the most hazardous severe icing events for aircraft occur under sustained synoptic lifting, where prolonged exposure leads to progressive ice accretion and gradual degradation of aerodynamic performance.

In the context of the Voepass accident, Figure 7 provides a direct dynamic link to the observations described in the CENIPA preliminary report. The report describes a sequence of performance degradation alerts occurring over a relatively extended time interval, without indication of an abrupt change in meteorological regime. The presence of the 500 hPa trough suggests that the atmospheric environment responsible for icing remained active and sustained throughout the critical period, consistent with the progressive nature of the degradation observed in the aircraft.

Furthermore, the positioning of the trough axis over southeastern Brazil implies that the aircraft was operating ahead of the system’s axis, a region classically associated with upward motion and the maintenance of thick cloudiness (Bluestein, 1993; Sprenger et al., 2013). This pattern reinforces the interpretation that there was no

“clear window” of meteorological escape at mid-levels along the route at that time, increasing the likelihood of continuous exposure to the severe icing conditions indicated at lower levels.

Figure 8 presents the wind field at 250 hPa at 16:00 UTC on August 9, 2024, highlighting the presence of a well-defined jet over southern and southeastern Brazil during the critical phase of Flight 2283. A core of strong winds is observed, with isotachs exceeding $40\text{--}50\text{ m s}^{-1}$, extending from northern Argentina toward the South Atlantic, crossing southern Brazil and directly influencing the state of São Paulo.

The spatial configuration of the jet indicates that the Cascavel–Guarulhos flight corridor lies under the influence of a dynamically active sector of the upper-level flow. The curvature of the flow and the velocity gradient suggest the presence of regions favorable for upper-level divergence, particularly associated with jet exit regions. This upper-level divergence is consistent with the upward motion observed at 700 hPa (Figure 6) and with the maintenance of the mid-level trough (Figure 7).

The persistence of this upper-level pattern during the flight time window indicates that dynamic support for atmospheric lifting remained active throughout the entire critical period, favoring the continuity of cold cloudiness and thermodynamic conditions conducive to in-flight icing formation.

The presence of an intense jet at 250 hPa over the accident region, as shown in Figure 8, completes the picture of vertical dynamic coupling responsible for sustaining the adverse meteorological environment. The literature on synoptic and aviation meteorology highlights that upper-level divergence associated with jet streak exit regions plays a fundamental role in intensifying and maintaining frontal systems and mid-level troughs, promoting persistent upward motion of the air mass below (Bluestein, 1993; Sprenger et al., 2013; Gultepe et al., 2019).

This mechanism is particularly relevant for severe in-flight icing formation, as continuous lifting favors the replenishment of supercooled liquid water droplets within cold stratiform clouds, maintaining hazardous conditions over extended periods (Bernstein et al., 2005; Cao et al., 2015). Unlike transient convective events, environments sustained by upper-level jets tend to produce persistent and diffuse icing, which is often more difficult to detect and avoid operationally.

In the context of the Voepass accident, the report describes a sequence of performance degradation alerts occurring over several minutes, without indication of an abrupt change in meteorological conditions. The presence of a well-established upper-level jet suggests that the adverse atmospheric environment was continuously reinforced, reducing the likelihood of rapid dissipation of icing conditions along the route.

Furthermore, the combined influence of the jet at 250 hPa, the trough at 500 hPa (Figure 7), and the ascent at 700 hPa (Figure 6) indicates a scenario of strong vertical coupling across tropospheric levels, a condition frequently reported in international case studies of severe in-flight icing associated with serious accidents and incidents (Golding, 2004; Cao & Xin, 2020; Bromfield et al., 2023). This type of dynamic environment significantly increases the risk of prolonged aircraft exposure to severe icing, particularly during cruise operations of turboprop aircraft within the critical altitudinal range.

Figure 9 presents the temporal evolution of cloudiness observed by satellite in the infrared channel during the critical window of Flight 2283. At 15:00 UTC (Figure 9a), an extensive band of continuous cloud cover is observed over southern and southeastern Brazil, with relatively low brightness temperatures, indicative of high and cold cloud tops. The flight trajectory directly intersects this cloud band already during the early cruise phase. Between 15:30 and 16:00 UTC (Figures 9b and 9c), the cloud field remains organized and nearly stationary over the Cascavel–Guarulhos flight corridor. Brightness temperatures remain homogeneous and persistently low, suggesting the presence of a predominantly stratiform system, with no clear indication of isolated deep convection. This pattern indicates an environment of extensive and continuous cloudiness, in which the aircraft remains embedded for a prolonged period.

At 16:30 and 17:00 UTC (Figures 9d and 9e), a period that coincides with the intensification of the performance degradation described in the CENIPA preliminary report, the aircraft is still located beneath the same cold cloud structure, with no evidence of significant dissipation or fragmentation of the system. The spatial persistence of the cloud field along the entire route suggests that there were no evident clear corridors for lateral deviation at synoptic or mesoscale scales.

These results indicate that, throughout the entire critical operational window, the flight remained embedded within an environment of extensive cold cloudiness, consistent with deep stratiform clouds associated with frontal systems.

The satellite observations presented in Figure 9 provide fundamental evidence for interpreting the accident, as they visually confirm the persistence of the atmospheric environment inferred from the dynamical and thermodynamical analyses (Figures 4 to 8). The literature on in-flight icing highlights that the most hazardous scenarios for turboprop aircraft are not necessarily associated with intense convection, but rather with extensive cold stratiform cloud fields in which supercooled liquid water can be sustained for long periods (severe in-cloud icing) (Bernstein et al., 2005; Golding, 2004; Gultepe et al., 2019).

In this context, the homogeneity and continuity of the cloud field observed in the infrared channel are particularly relevant. Unlike isolated convective cells, which could be avoided through relatively small lateral deviations, stratiform systems associated with cold fronts tend to cover large areas, significantly reducing operational escape options (Politovich, 1989; Cao et al., 2015). Figure 9 suggests that Flight 2283 crossed such an environment, remaining embedded within cloud cover throughout most of the critical time window.

This interpretation is consistent with the CENIPA report, which describes a progressive degradation of aircraft performance, with successive alerts of airspeed reduction and aerodynamic degradation, rather than an abrupt event associated with a specific convective cell. The persistence of cold cloudiness observed in satellite imagery supports the hypothesis of prolonged exposure to in-cloud icing, a mechanism widely documented as a precursor to loss of control in flight (LOC-I) events in turboprop aircraft (Lynch & Khodadoust, 2001; Cao & Xin, 2020; Bromfield et al., 2023).

Furthermore, the temporal coincidence between the aircraft's presence beneath the coldest cloud tops (15:00–17:00 UTC) and the operational records from CENIPA reinforces the active role of meteorological conditions in the chain of events leading to the accident. Satellite observations not only confirm the presence of cloud cover but also demonstrate that the adverse atmospheric environment was spatially continuous and temporally persistent, key characteristics for the development of cumulative severe icing.

Figure 10 presents the fields of reflectivity (dBZ), differential reflectivity (ZDR), and specific differential phase (KDP). At 1500 UTC (Figures 10a, 10c, and 10e), the aircraft was embedded within an extensive area of continuous meteorological echoes, with reflectivity values predominantly between 10 and 30 dBZ. No intense convective cores or localized structures with reflectivity exceeding 40 dBZ are identified along the flight trajectory. The ZDR field shows values generally close to 0 dB to slightly positive, with moderate spatial variability, while KDP remains low and relatively homogeneous over the analyzed region, indicating the absence of organized intense precipitation in the immediate vicinity of the aircraft.

At 15:15 UTC (Figures 10b, 10d, and 10f), the system structure maintains a similar spatial pattern, indicating persistence of the precipitation field over the area crossed by the flight. Reflectivity remains predominantly at weak to moderate levels, with no development of organized convective cells or abrupt intensification of echoes near the aircraft's position. The ZDR and KDP fields remain consistent with those observed fifteen minutes earlier, showing no systematic increase that would indicate a significant change in the microphysical structure of the precipitation during the analyzed interval. The observed values of the three variables (ZDR near 0, reflectivity

below 30 dBZ, and KDP below $1^{\circ} \text{ km}^{-1}$) indicate the absence of hail along the aircraft trajectory, and that the route followed shortly before the accident is consistent with a cold stratiform environment potentially favorable to the presence of supercooled liquid water, with light to moderate rain at flight level (Straka et al., 2000).

Considering the 1.6° elevation angle and the approximate distances between the aircraft and the radar (~150 to ~210 km during the analyzed times), it is estimated that the radar beam was intercepting atmospheric levels between approximately 4 km and 6 km altitude, close to the flight level FL170 (~5.2 km). Overall, the radar data indicate that the aircraft operated under a spatially continuous and structurally stable precipitation regime between 15:00 and 15:15 UTC, with no evidence of localized deep convection along the trajectory. This pattern is consistent with the frontal configuration identified in the synoptic analyses and satellite imagery, reinforcing the interpretation that the flight occurred within a broad and organized meteorological environment during the critical operational window.

The radiosonde observation conducted at 12:00 UTC on August 9, 2024, at Campo de Marte Aerodrome (SBMT) (Figure 11) provides direct observational evidence of the thermodynamic structure of the atmosphere prior to the departure of Flight 2283. The vertical profile indicates the presence of a deep layer with subfreezing temperatures and high relative humidity, extending approximately from levels near 850 hPa to above 300 hPa, characterizing an environment favorable for the formation of thick cold cloud layers.

It is observed that the flight level FL170, corresponding to approximately 500–550 hPa, is embedded within this cold and nearly saturated layer, with temperatures on the order of -10 to -15°C —a thermodynamic range classically associated with in-flight icing. The agreement between the radiosonde profile, atmospheric reanalysis fields, and satellite imagery reinforces the interpretation that the environment favorable for severe icing was already established prior to takeoff and persisted throughout the critical operational window of the flight, consistent with the descriptions presented in the CENIPA preliminary report.

The integrated analysis of atmospheric conditions allows for the assessment of the role of the FL170 flight level as a central element in the aircraft's exposure to the adverse meteorological environment. As evidenced by the

radiosonde and reanalysis fields, FL170 is located within a layer characterized by persistent subfreezing temperatures and high humidity, corresponding to the thermodynamic range most favorable for in-flight icing. The prolonged persistence of the aircraft at this level implies continuous exposure to critical atmospheric conditions, particularly within an environment dominated by deep and sustained stratiform cloudiness. In this context, the absence of a rapid transition to thermodynamically warmer or drier layers suggests that the flight remained embedded within the core region of highest icing potential for most of the critical operational window, consistent with the descriptions presented in the CENIPA preliminary report.

Figure 12 presents the thermodynamic profile of the atmosphere over the region of interest during the accident period, allowing for the analysis of the vertical structure of temperature and humidity. A deep layer of subfreezing temperatures is observed, extending approximately from levels near 850 hPa to above 600 hPa, with temperature values ranging between 0 °C and –20 °C. Within this layer, a small separation between the temperature and dew point curves is noted, indicating high relative humidity and near-saturated conditions.

The aircraft's flight level (FL170) is clearly embedded within this cold and moist layer, coinciding with the temperature range classically associated with in-cloud icing. The vertical depth of this layer suggests an environment favorable not only for the occurrence of icing but also for its persistence over time, as small vertical variations in altitude would not be sufficient to remove the aircraft from the critical region.

Furthermore, the profile does not exhibit pronounced temperature inversions that could limit the vertical development of cloudiness, indicating an atmosphere conducive to the formation of deep cold stratiform clouds. This pattern is consistent with the satellite imagery (Figure 9) and with the humidity and vertical motion fields observed at 700 hPa (Figure 6).

The thermodynamic profile shown in Figure 12 provides one of the most direct pieces of evidence that Flight 2283 was operating within an environment classically favorable for severe in-flight icing. The literature establishes that the temperature range between approximately 0 °C and –20 °C, when combined with high relative humidity, represents the most critical interval for the presence of supercooled liquid water and for aerodynamic ice accretion (Politovich, 1989; Bernstein et al., 2005; Cober & Isaac, 2012).

The location of FL170 within this layer is particularly relevant in light of the CENIPA preliminary report, which indicates that the aircraft remained in cruise at this level while successive performance degradation alerts were recorded. The vertical depth of the cold and saturated layer suggests that the aircraft was exposed for a prolonged period to conditions favorable for progressive ice accretion, reducing the effectiveness of simple altitude-change strategies as an immediate mitigation measure.

International case studies involving ATR aircraft and other turboprops show that environments with deep layers of icing potential are particularly hazardous, as they favor the formation of mixed and clear ice, types known to produce greater increases in drag and reductions in lift, and which are more difficult to remove by conventional de-icing systems (Lynch & Khodadoust, 2001; Cao et al., 2015; Cao & Xin, 2020). This mechanism is consistent with the pattern described by CENIPA, in which performance degradation occurs gradually, culminating in loss of control in flight (LOC-I), without evidence of an abrupt or isolated meteorological event.

The absence of significant dry layers or abrupt discontinuities in the thermodynamic structure reinforces the interpretation that the adverse atmospheric environment was continuous and persistent, consistent with the extensive cloudiness observed in satellite imagery and with the dynamic support identified at mid and upper levels (Figures 7 and 8). This set of evidence points to a typical severe in-cloud icing scenario, widely documented in the literature as a contributing factor in aircraft accidents involving loss of control during cruise (Gultepe et al., 2019; Bromfield et al., 2023).

Figure 13 presents a vertical cross-section of the atmosphere along the Cascavel–Guarulhos route during the critical period of Flight 2283, allowing an integrated visualization of the spatial and vertical distribution of temperature and relative humidity. An extensive and continuous layer of cold air, with subfreezing temperatures, is observed extending from western Paraná to the interior of São Paulo State, covering a large portion of the corridor traversed by the aircraft.

This cold layer exhibits high relative humidity, frequently exceeding 80%, within a vertical range approximately between 800 and 600 hPa, coinciding with the temperature interval between 0 °C and –20 °C. The aircraft’s flight level (FL170) is embedded within this layer along a significant portion of the route, indicating prolonged exposure to an environment thermodynamically favorable for in–cloud icing.

The spatial continuity of this layer over hundreds of kilometers suggests that the adverse atmospheric conditions were not confined to a localized sector but rather constituted a persistent atmospheric corridor. No dry layers or positive isotherms are observed along the cross-section that would indicate a clear vertical escape route within moderate altitude variations.

The vertical cross-section shown in Figure 13 provides key evidence for understanding the persistent nature of the meteorological environment encountered by Flight 2283. Unlike situations in which in-flight icing occurs locally or is associated with isolated convective cells, the presence of a continuous cold and saturated layer along much of the route is characteristic of severe in-cloud icing events associated with stratiform frontal systems (Politovich, 1989; Bernstein et al., 2005; Gultepe et al., 2019).

This type of vertical structure is particularly hazardous for turboprop aircraft, as it favors prolonged exposure to supercooled liquid water droplets, allowing progressive ice accretion even with ice protection systems activated (Lynch and Khodadoust, 2001; Cao et al., 2015). Figure 13 suggests that, for a significant portion of the flight, the aircraft remained within a critical atmospheric layer without an immediate vertical alternative to fully exit the hazardous environment.

This evidence aligns directly with the CENIPA preliminary report, which describes a sequence of progressive performance degradation while the aircraft remained in cruise at FL170. The absence of abrupt changes in the vertical profile along the route reinforces the interpretation that ice accretion occurred continuously, rather than as a result of a brief incursion into a localized meteorological feature.

Furthermore, Figure 13 reinforces the coupling between the results presented in previous figures. The cold and moist layer observed along the route is dynamically sustained by the mid-level trough (Figure 7) and the upper-level jet (Figure 8), while its observable manifestation is confirmed by the extensive cloudiness detected in satellite imagery (Figure 9). This set of evidence consolidates the interpretation that Flight 2283 operated within a structurally organized and persistent adverse meteorological environment.

Figure 14 presents the spatial distribution of temperature and relative humidity at the 700 hPa level between 1500 and 1700 UTC on August 9, 2024. This level represents the mid-tropospheric layer where persistent upward motion and thermodynamic conditions favorable for the maintenance of supercooled liquid water were observed. Throughout the analyzed period, the flight trajectory is embedded within a region characterized by subfreezing temperatures,

predominantly between -5°C and -15°C , associated with high relative humidity values.

At 1500 UTC (Figure 14a), the Cascavel–Guarulhos flight corridor is already under thermodynamic conditions favorable for in-flight icing, with an extensive area of cold and moist air covering western Paraná and advancing toward the interior of São Paulo State. Between 16:00 and 17:00 UTC (Figures 14b and 14c), a period that coincides with the intensification of performance degradation alerts described in the CENIPA report, this area remains nearly stationary, encompassing the entire critical segment of the flight.

The spatial persistence of this environment at flight level indicates that the aircraft remained continuously exposed to conditions favorable for icing, with no evidence of thermal or moisture gradients that would suggest a rapid lateral exit from the adverse field. This pattern reinforces the interpretation of a homogeneous and extensive atmospheric environment at the aircraft's operational level.

The analysis of meteorological conditions at the level equivalent to FL170 shown in Figure 14 provides particularly robust evidence of the role of meteorology in the accident, as it eliminates the need for significant vertical extrapolation. The literature on in-flight icing emphasizes that evaluating conditions at the exact flight level is essential for understanding the severity of the phenomenon, since small vertical displacements can significantly alter the type and intensity of icing (Politovich, 1989; Bernstein et al., 2005; Cober & Isaac, 2012).

The pattern observed in Figure 14, moderately subfreezing temperatures combined with high relative humidity, is characteristic of environments conducive to in-cloud icing, particularly mixed and clear ice, which are considered the most critical from an aerodynamic perspective (Lynch & Khodadoust, 2001; Cao et al., 2015). The persistence of the aircraft within this environment throughout the critical period is consistent with the progressive nature of the performance degradation described by CENIPA, which reports successive alerts of airspeed reduction and aerodynamic degradation prior to the loss of control in flight.

Moreover, the extensive area of favorable conditions observed at flight level suggests that modest lateral deviations would likely not have been sufficient to remove the aircraft from the adverse environment, an operational aspect widely discussed in international case studies of severe in-flight icing associated with stratiform frontal systems (Golding, 2004; Gultepe et al., 2019; Bromfield et al., 2023). This factor is particularly relevant for aircraft in cruise, as it limits the mitigation options available to the flight crew in real time.

Figure 14 also reinforces the consistency across the different levels of analysis presented in this study. The cold and moist environment identified at flight level is sustained by the ascent observed at 700 hPa (Figure 6), the mid-level trough (Figure 7), and the dynamic support of the upper-level jet (Figure 8), and is also manifested

observationally as extensive cloudiness in satellite imagery (Figure 9). This multiscale consistency strengthens the interpretation that Flight 2283 was embedded within an organized and persistent atmospheric system favorable to the formation of severe icing on aircraft control surfaces.

4. DISCUSSION AND CONCLUSIONS

This study analyzed the meteorological environment associated with the Voepass Flight 2283 accident that occurred on August 9, 2024, using an integrated approach based on atmospheric reanalysis data, satellite imagery, and observed radiosonde data, in accordance with the operational information provided in the CENIPA preliminary report. The analysis was conducted in a multiscale framework, allowing for a consistent characterization of the synoptic, dynamic, and thermodynamic conditions acting during the critical phase of the flight.

The results indicate that the event occurred under the influence of a well-defined frontal system, associated with strong cold air advection at low levels, a mid-level trough, and dynamic support at upper levels, an atmospheric configuration frequently linked to the formation of extensive cold stratiform cloud fields. This synoptic setup favored the maintenance of a deep layer characterized by subfreezing temperatures and high relative humidity, a condition classically associated with in-flight icing.

Satellite-based observational analysis confirmed the spatial and temporal persistence of cold cloudiness along the aircraft's route, while the radiosonde launched at Campo de Marte at 12 UTC provided direct and independent evidence that the critical thermodynamic structure was already established prior to departure. The vertical profile indicated an extensive, nearly saturated layer encompassing the FL170 flight level, with temperatures within the range most favorable for severe icing formation.

Vertical cross-sections and atmospheric fields at the level equivalent to FL170 demonstrated that the aircraft remained embedded, for most of the critical operational window, within a continuous atmospheric corridor of cold and moist air, with no significant vertical or horizontal gradients that would allow a rapid exit from the adverse environment. This spatial persistence of the critical layer reinforces the interpretation that exposure to supercooled liquid water and icing conditions occurred in a prolonged and progressive manner, rather than as a result of a brief incursion into a localized meteorological feature.

The set of meteorological evidence presented is consistent with the records of progressive performance degradation described by CENIPA and with patterns documented in the literature on accidents and incidents involving turboprop aircraft under icing conditions. In this context, the results reinforce the role of meteorology

as a relevant contributing factor in the chain of events, by characterizing an atmospheric environment that was structurally organized and persistently favorable to in-flight icing.

Finally, this study contributes to the understanding of atmospheric mechanisms associated with severe icing events in regional aviation operations, highlighting the importance of integrating multiple meteorological data sources in the investigation and prevention of aircraft accidents. Future studies may incorporate weather radar data and more detailed microphysical analyses in order to further characterize the three-dimensional structure of clouds associated with this type of event.

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Author contributions

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Competing interests

The authors declare no competing interests.

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FIGURE LIST

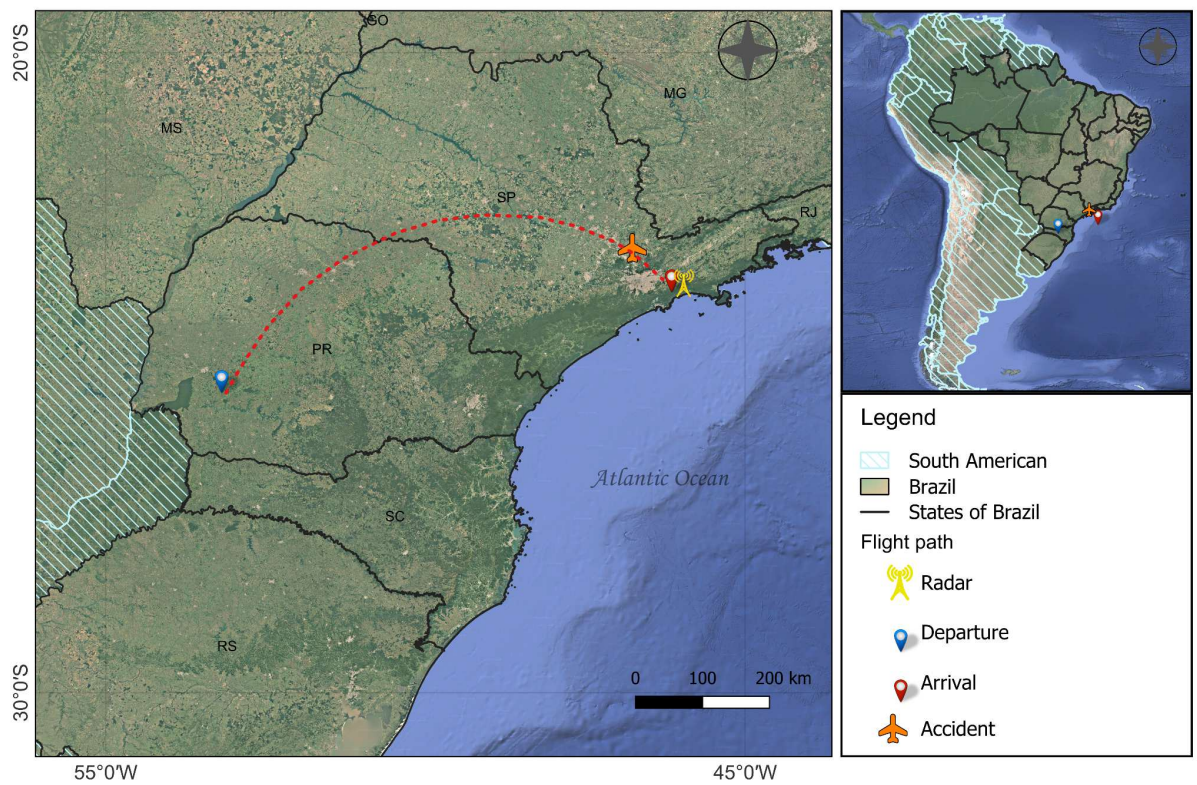


Figure 1 | Study area and flight route of Flight 2283. The accident site is marked with an orange aircraft symbol.



Figure 2. ATR 72-500 aircraft (PS-VPB) operated by VOEPASS Linhas Aéreas. Source: Meier (2022).

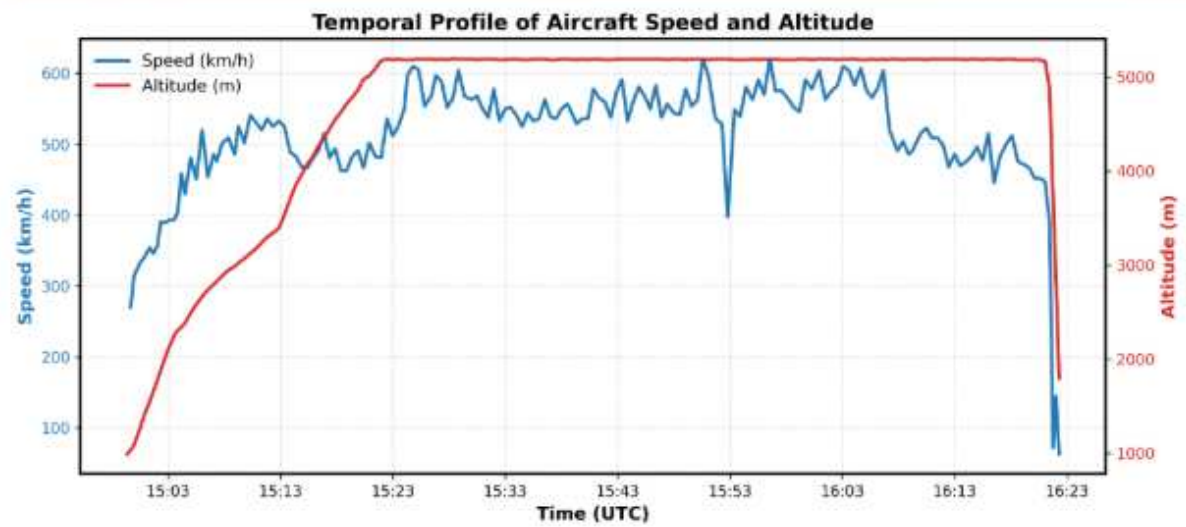
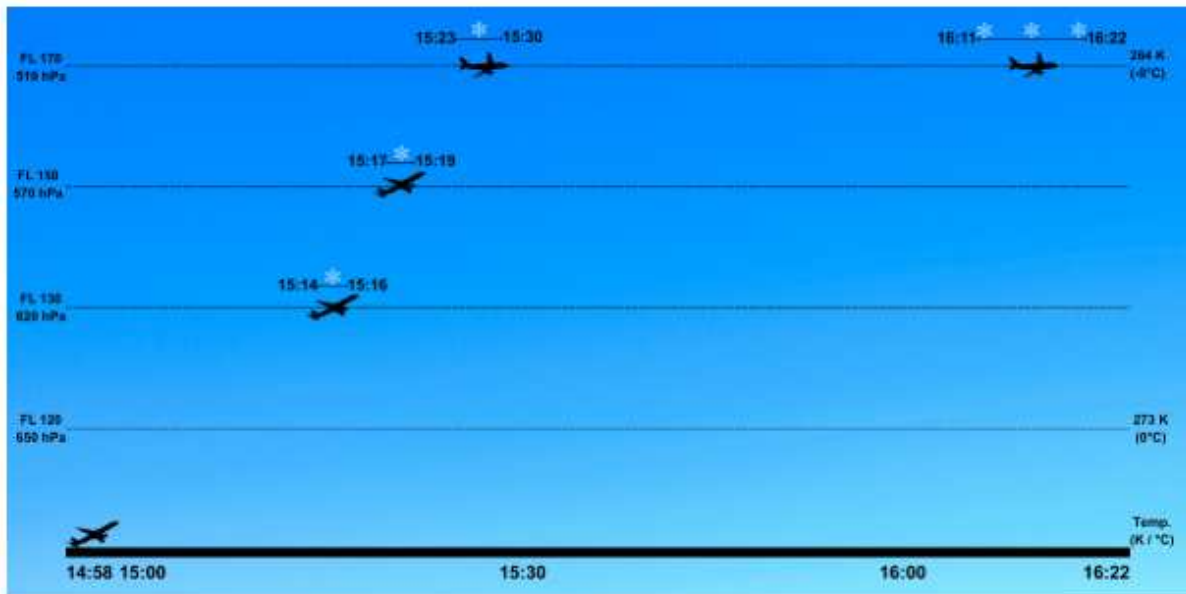


Figure 3 | Temporal and vertical evolution of Flight 2283 during the critical operational window: (a) schematic representation of the altitudinal progression and icing detection records; (b) observed temporal profile of altitude and velocity (UTC).

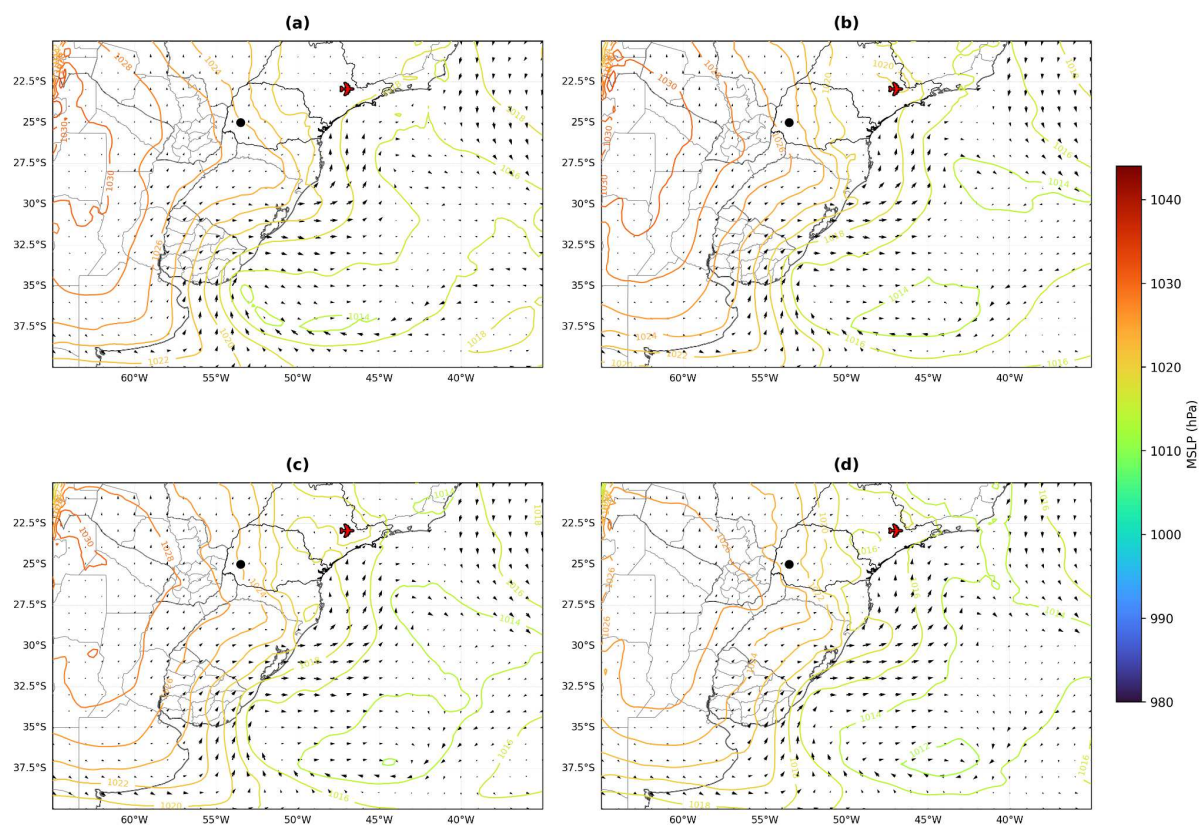


Figure 4 | Mean sea level pressure (MSLP, hPa) and 10-m wind on August 9, 2024: (a) 1200 UTC, (b) 1500 UTC, (c) 1600 UTC, and (d) 1800 UTC. The black dot indicates the departure location.

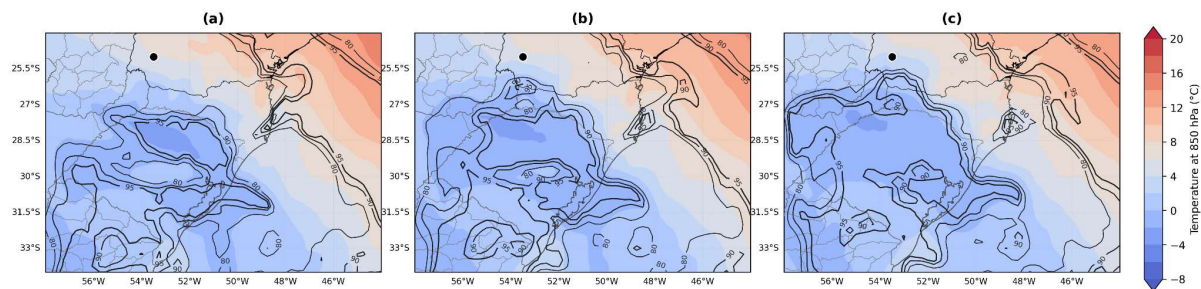


Figure 5 | Temperature (°C, shaded) and relative humidity (% , contours) at 850 hPa at (a) 15:00 UTC, (b) 16:00 UTC, and (c) 17:00 UTC on August 9, 2024.

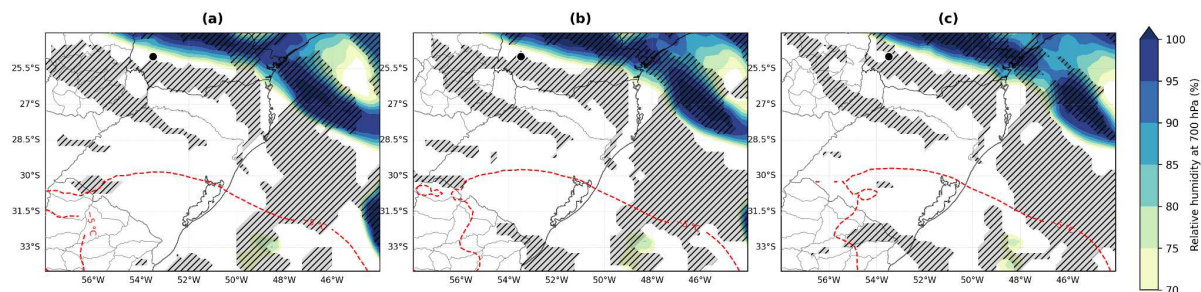


Figure 6 | Relative humidity (% , shaded), regions of ascent (hatched; $\omega < 0$), and the -5°C isotherm at 700 hPa at (a) 15:00 UTC, (b) 16:00 UTC, and (c) 17:00 UTC on August 9, 2024.

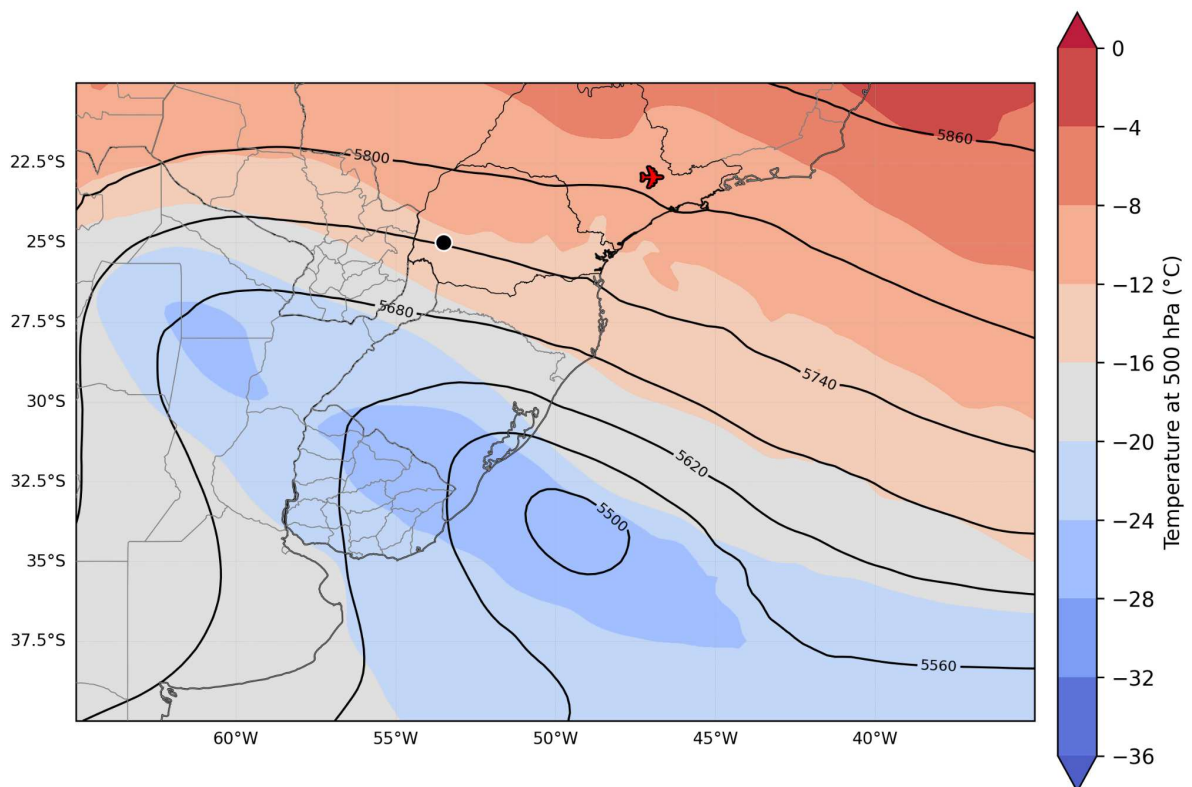


Figure 7 | Geopotential height (m, contours) and temperature (°C, shaded) at 500 hPa at 16:00 UTC on August 9, 2024.

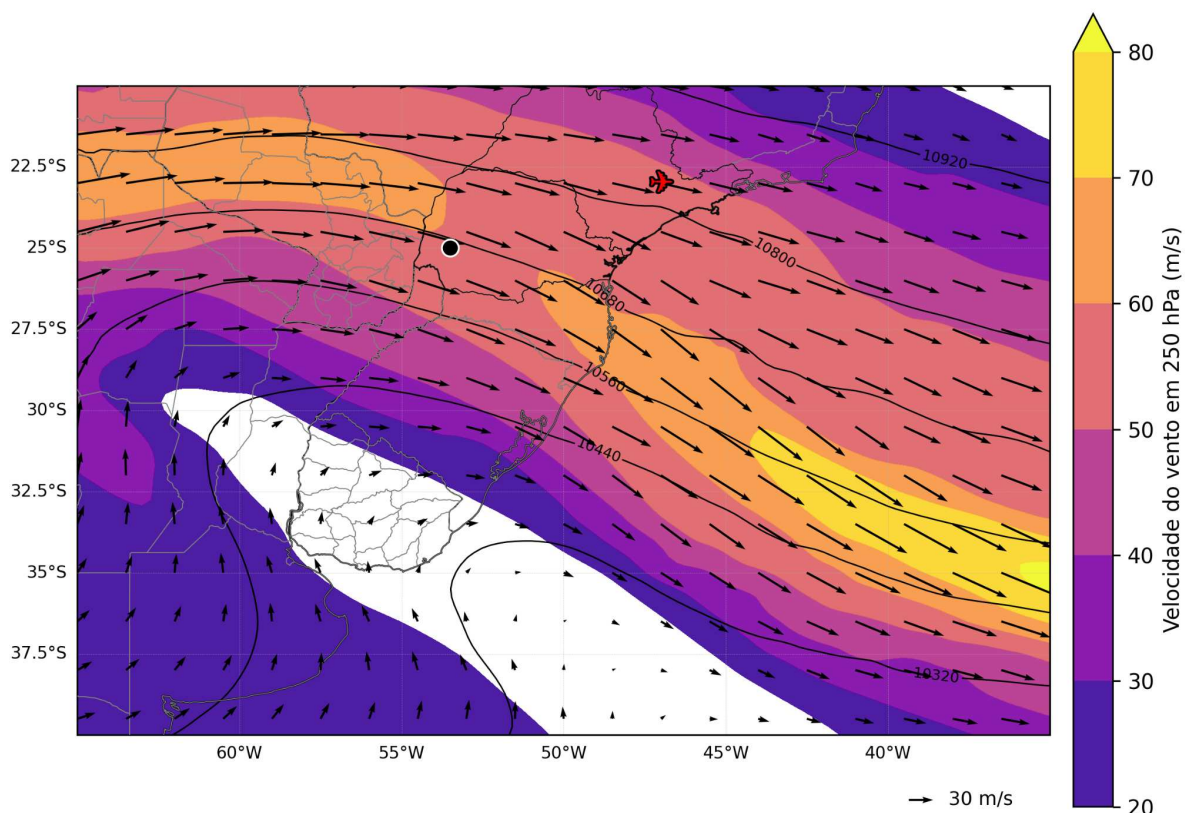


Figure 8 | Wind speed (isotachs, m s^{-1}) and flow at 250 hPa at 16:00 UTC on August 9, 2024.

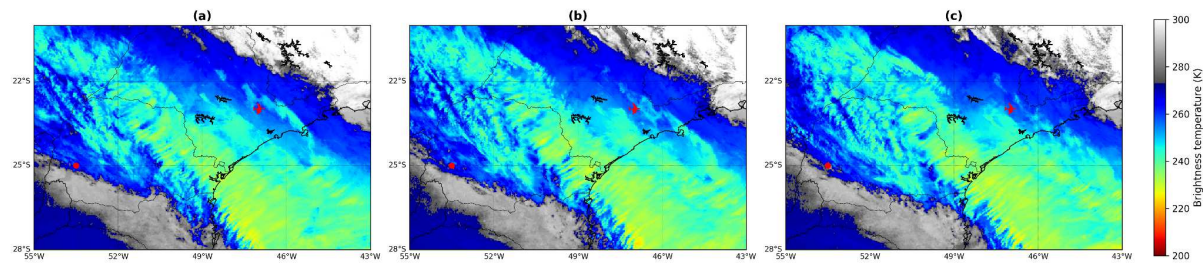


Figure 9 | Infrared brightness temperature (K; shaded) at: (a) 15:30 UTC, (b) 16:10 UTC, and (c) 16:40 UTC on August 9, 2024.

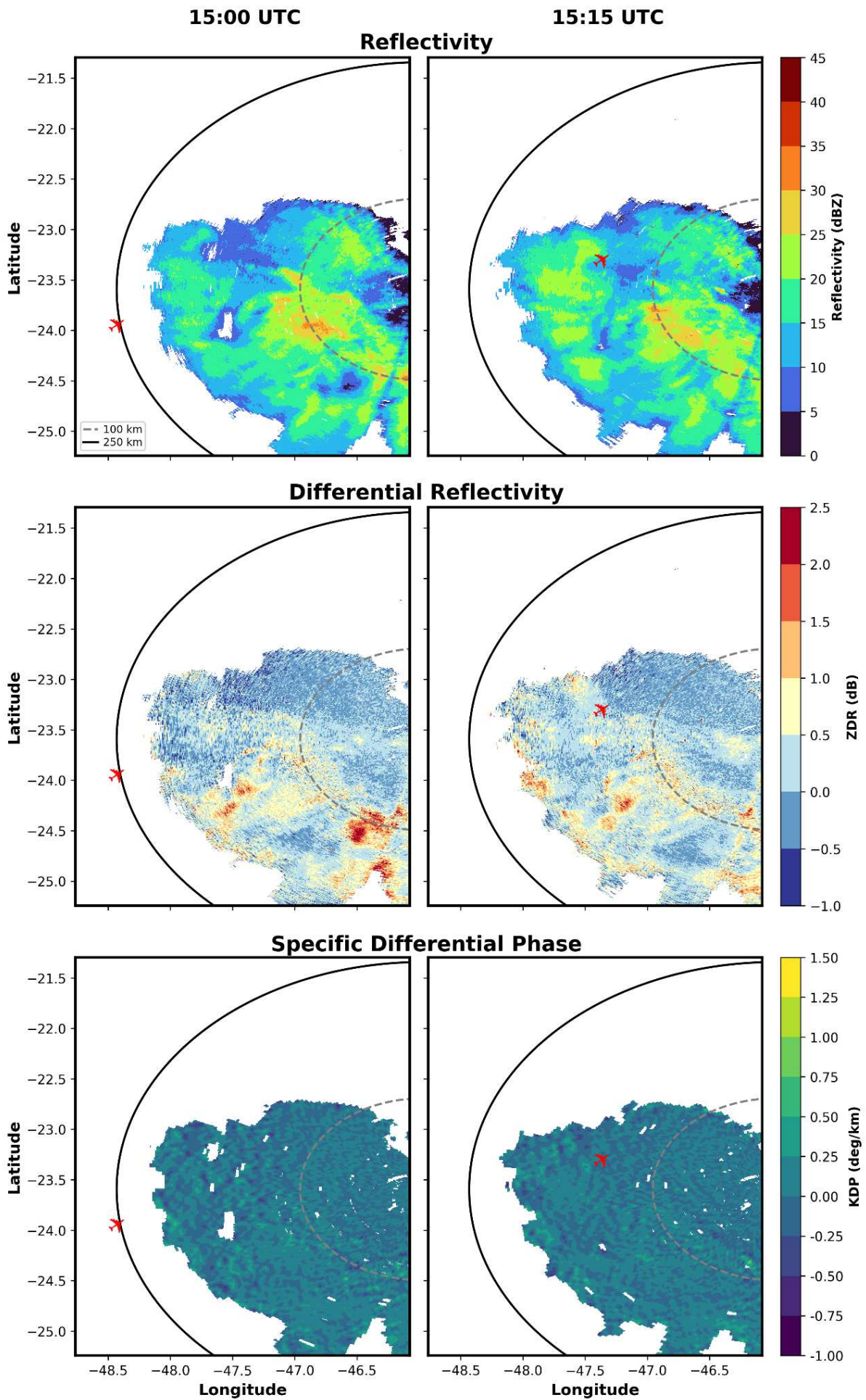


Figure 10 | Reflectivity (dBZ), differential reflectivity (ZDR), and specific differential phase (KDP) fields obtained from the S-band polarimetric radar in Salesópolis (CTH), in PPI at 1.6°, at 15:00 and 15:15 UTC on August 9, 2024. Range rings correspond to 250 km (solid) and 100 km (dashed).

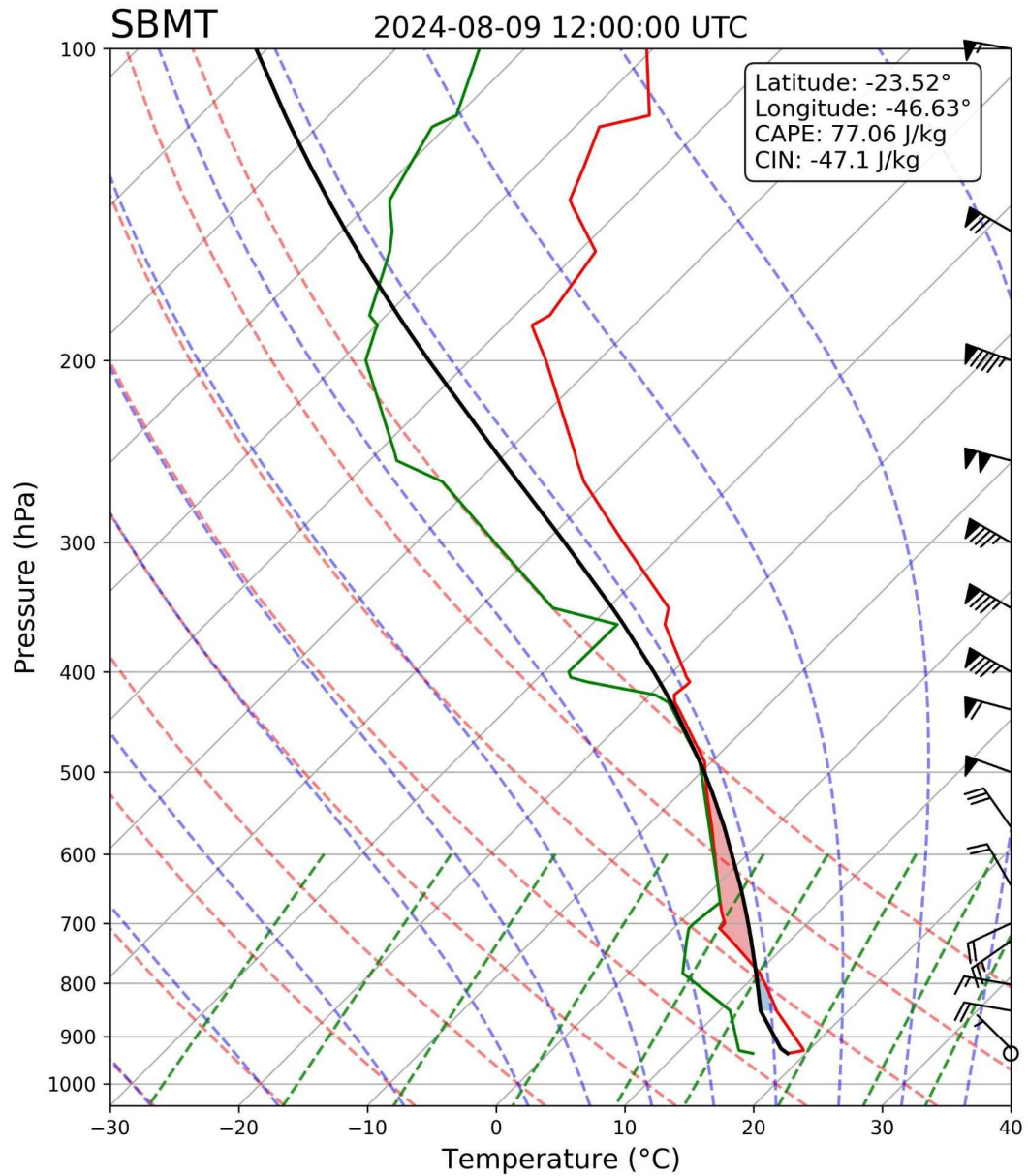


Figure 11 | Skew-T log-P thermodynamic diagram from the radiosonde launched at 12:00 UTC on August 9, 2024, at Campo de Marte Aerodrome (SBMT). The profile shows a deep cold and nearly saturated layer, with subfreezing temperatures from low levels to the mid-troposphere, encompassing the FL170 flight level, conditions favorable for in-flight icing.

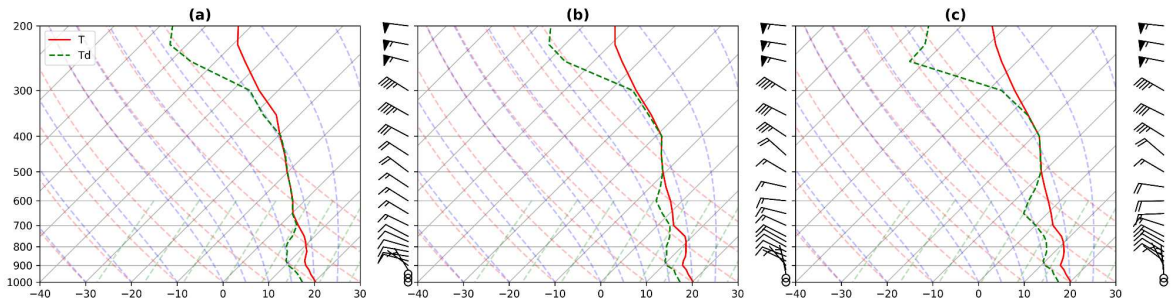


Figure 12 | Vertical profiles of temperature ($^{\circ}\text{C}$, solid line) and dew point ($^{\circ}\text{C}$, dashed line) derived from ERA5 at (a) 15:00 UTC, (b) 16:00 UTC, and (c) 17:00 UTC on August 9, 2024, shown in Skew-T log-p diagrams for the reference point near Vinhedo (SP).

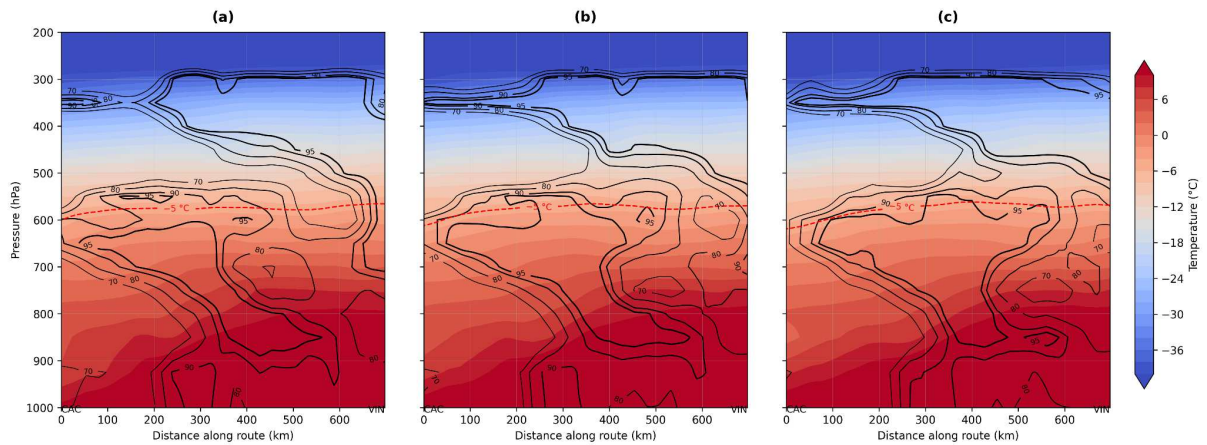


Figure 13 | Vertical cross-section of temperature ($^{\circ}\text{C}$, shaded) and relative humidity (% , contours) along the Cascavel/PR–Vinhedo/SP route, derived from ERA5, at (a) 1500 UTC, (b) 1600 UTC, and (c) 1700 UTC on August 9, 2024.

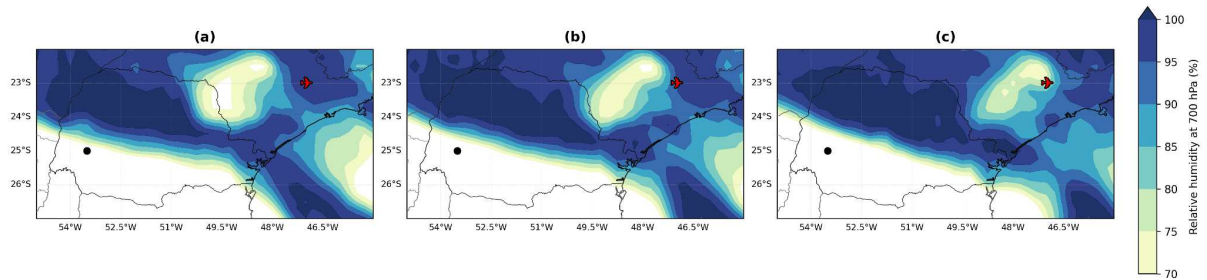


Figure 14 | Relative humidity (% , shaded) and the -5°C isotherm at 700 hPa derived from ERA5 over the operational domain (CAC–SP) at (a) 1500 UTC, (b) 1600 UTC, and (c) 1700 UTC on August 9, 2024.